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# Fault Tree Analysis and Extensions of the V/L Process Structure

Lisa K. Roach

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## **1. Introduction**

The Ballistic Vulnerability/Lethality Division (BVLD), Survivability/Lethality Analysis Directorate (SLAD) of the Army Research Laboratory (ARL) is involved in a variety of programs that require detailed information about the required capabilities of combat equipment. First, the BVLD is conducting a series of full-scale vulnerability tests on a number of combat systems. Prior to these full-scale tests, analytical vulnerability analyses are performed to aid in the development of the test plan and to provide insights into possible outcomes. In addition, the BVLD is implementing the Degraded States Vulnerability Methodology (DSVM) for a variety of combat systems (Abell, Roach, Starks, 1989; Abell, Burdeshaw, Rickter, 1990). Both efforts require information on the capabilities of the combat system to perform mission-essential functions. To satisfy this requirement, the BVLD conducts component-level vulnerability analyses on subsystems of the target, which, if damaged, can affect the performance of one or more of the system's combat functions (Ploskonka, Muehl, and Dively, 1988). These component-level vulnerability analyses employ fault tree analysis to describe, at the component level, system capabilities and capability levels. This report describes the use of fault tree analysis within the vulnerability/lethality (V/L) framework and discusses applications in other areas as well as future efforts/requirements.

## **2. V/L Process Structure**

To understand the value of fault tree analysis one first must have an appreciation of the Vulnerability/Lethality taxonomy as defined by Klopke, Starks, and Waibert (1992). A brief discussion is provided here.

The basis for the taxonomy of V/L Spaces comes from the recognition that V/L analyses pass through distinct levels of information in a precise order. These levels are:

Level 1: Threat-Target Interaction, or Initial Configuration  
(including Initial Conditions),

Level 2: Target Component Damage States,

Level 3: Target Capability States, and

Level 4: Target Combat Utility.

From the Target Capability States can be derived the various mission-oriented losses of function such as "Firepower Kill" and "Mobility Kill".

The mappings by which one passes from one level to the next are dependent on different kinds of information at each level. For example, going from Level 1 to Level 2 (threat-target initial configuration to target damage) essentially involves physics; going from Level 2 to Level 3 (target damage to capability) requires engineering measurement. The process is shown pictorially in Figure 1.

It is important at the outset to differentiate between "Levels", which are composed only of states of existence, and the "mappings", operators -- with the data and algorithms to which they have access -- which relate a state at one level to a state at another.

A *Level* contains all the information required to define the state of the system at the associated stage of a V/L analysis/experiment. At each level, one can define a space of points, each point being a vector whose elements correspond to the status of a particular entity related to the target. For example, in Space 2 (Damage States), each element may refer to the status of a particular component/subsystem. The spaces thus defined are the "V/L Spaces", and represent, at each level, the state of the target system.

A *Mapping* represents all of the information (physics, engineering, etc.), known or unknown, required to associate a point in a space at one level with a point in a space at the next level. Mappings have access to information such as: fundamental data (penetration parameters [Level 1 to Level 2], leakage rates [Level 2 to Level 3], etc.); intermediate data generated by the mapping (line-of-sight thicknesses [1 to 2], temperature rise in an uncooled engine [2 to 3]); and algorithms (depth of penetration [1 to 2], fault trees [2 to 3] or [3 to 4]).

The V/L experimental and analytical processes can then be expressed as a series of mappings which relate a state vector in one space (the domain) to a resultant state vector in a next higher-level space (the range).

Note that at each transition to the next level, some detail about the target system may be lost: a broken bolt in Level 2 may be the cause of degraded mobility influencing mission effectiveness, but at Level 3, the bolt is no longer recognized as an entity. It is now widely acknowledged that skipping over levels (such as inferring remaining combat utility directly from the size of the hole in the armor) loses so significant an amount of information that continuity and auditability are lost.

As the taxonomy evolved, its application to areas other than V/L analyses were recognized. These areas include, but are not limited to, Reliability, Availability and Maintainability (RAM) and Battle Damage Repair (BDR) analyses; these will be the subject of discussion later in this paper.

# The Vulnerability Process

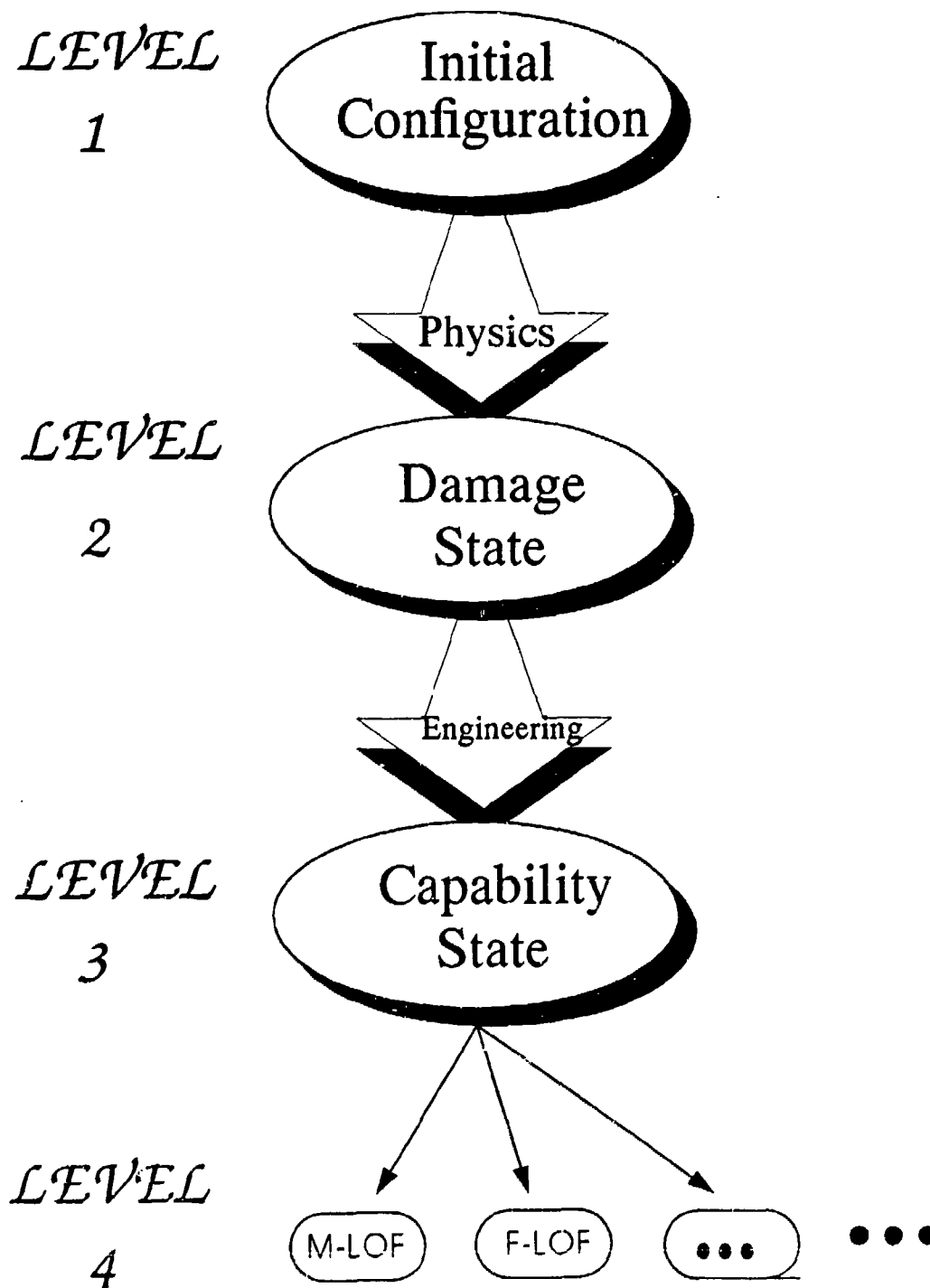


Figure 1. The Vulnerability/Lethality Process Structure

### 3. Criticality Analysis

Fault tree analysis, which is used at several levels within the V/L taxonomy just described, has its foundations in reliability theory (Ploskonka, Muehl, and Dively, 1988). First, one can think of a combat system as being composed of a number of systems where each system is a set of components. The performance of a component is binary; that is, the component has a value of "1" if it is functional and "0" if it is nonfunctional. (Note, binary functionality of components and systems is an assumption of the current set of models providing the foundation of this report. One could, given an appropriate continuous function, model functionality as a continuous process.) Additionally, one assumes pairwise independence of the components. Initially, the analytical determination of whether a particular system (or subsystem) is functional starts with connecting all of its components together in the form of a series/parallel construct; these constructs are normally referred to as fault trees. A construct listed in series will fail when at least one of its components fails. For a parallel construct, at least one component in each branch must fail in order for the construct to fail. Many systems, however, consist of both series and parallel constructs; here, a network diagram can be developed to show the functional relationship of the components. This network diagram indicates the system will function if one is able to trace a functioning path from top to bottom. Figure 2 provides examples of different fault tree configurations used by the BVLD; a later subject of this report will be the expansion of these forms to permit modeling of more complex systems. It is noted, though, that a number of sources of subjectivity enter into the process of determining these fault trees; a few are listed here for clarity:

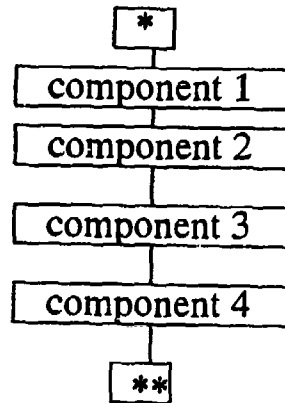
Which components should be included?

- how is this component defined?
- is it critical to system effectiveness?

What constitutes a system?

In vulnerability analysis, the just-described process is referred to as a criticality analysis. A fully functional combat system is analyzed system by system to determine which ones contribute directly to mission functions. Each system is described via a fault tree and, as indicated, is basically the determination of 1) which components, if lost, might result in a reduction of system capability, and 2) the structuring of these "critical" components into a fault tree format. The elements are assumed to be independent and the order within the fault tree is not important (though it should be noted that this assumption does not hold for more general Boolean constructs). The basic idea is to be able to trace a path from the top of the fault tree to the bottom. If no path is found, the functionality enabled by that set of components is lost.

### Series Fault Tree Structure



### Parallel Fault Tree Structure

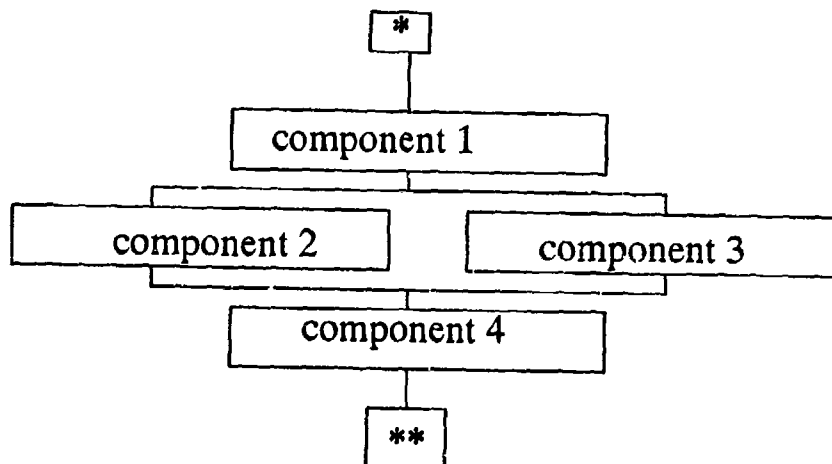


Figure 2. Examples of Fault Tree Configurations

A number of criticality analyses have been performed by the BVLD and a portion of one for an armored fighting vehicle (AFV) is provided here as an example. The analysis of the AFV (Ploskonka, Muehl, and Dively, 1988) was conducted with respect to three combat functions: mobility, firepower, and communications. These functions were further divided in the contributing systems for which fault trees were then developed. We will examine one of the subsystems within the mobility function; specifically, a requirement within the electrical power system. In developing the criticality analysis, Ploskonka et al. divided the electrical system into five subsystems, one of which was master power control. Master power control is the set of components required to control the flow of electricity to the vehicle and was determined to have parallel sources for turning on the vehicle master power. Both the commander and driver could turn it on; thus, both of these controls would have to be lost to cut supply of power to the entire vehicle. This functioning is reflected in a parallel construct in the fault tree by including the components for both the commander's and gunner's controls. Furthermore, two other components were deemed essential, the cable 2W103 and the hull networks box. The loss of either would result in loss of vehicle power; each was listed in the fault tree using a series construct. Figure 3 displays the fault tree developed for this subsystem.

This procedure is followed for each identified system. Smaller subsystems composed of critical components are developed first. These subsystems can then be combined in fault trees to represent higher order systems. For example, the master power control subsystem just discussed is part of a more sophisticated system representing electrical power. These fault trees are combined into progressively higher order systems until one sophisticated system is developed for each combat function identified.

The functioning of each system and subsystem is determined by consulting engineering blueprints and by talking to the contractors and the project managers. In their report, Ploskonka, Muehl, and Dively (1988) provide a more detailed discussion of the AFV criticality analysis.

#### **4. Capability Levels**

The criticality analysis provides input to live fire test planning in BVLD. It also provides the starting point for defining capability levels, or performance levels, for a combat system for use in the DSVM. The DSVM identifies the required functional capabilities of a combat system (i.e., mobility, firepower, acquisition, etc.). These required capabilities are then further divided into degraded capabilities, within each of the functional categories (i.e., reduced speed, reduced rate of fire, reduced acquisition, etc.), which describe varying degrees of degraded but operational states. Killed components/systems for a given target/warhead interaction are mapped into these degraded capabilities through fault tree analysis. This mapping permits calculation of the probabilities of the combat system being in one or more degraded capabilities. Table 1, provided as an example, lists capability levels for the mobility capability associated with an AFV.



## MASTER POWER CONTROL

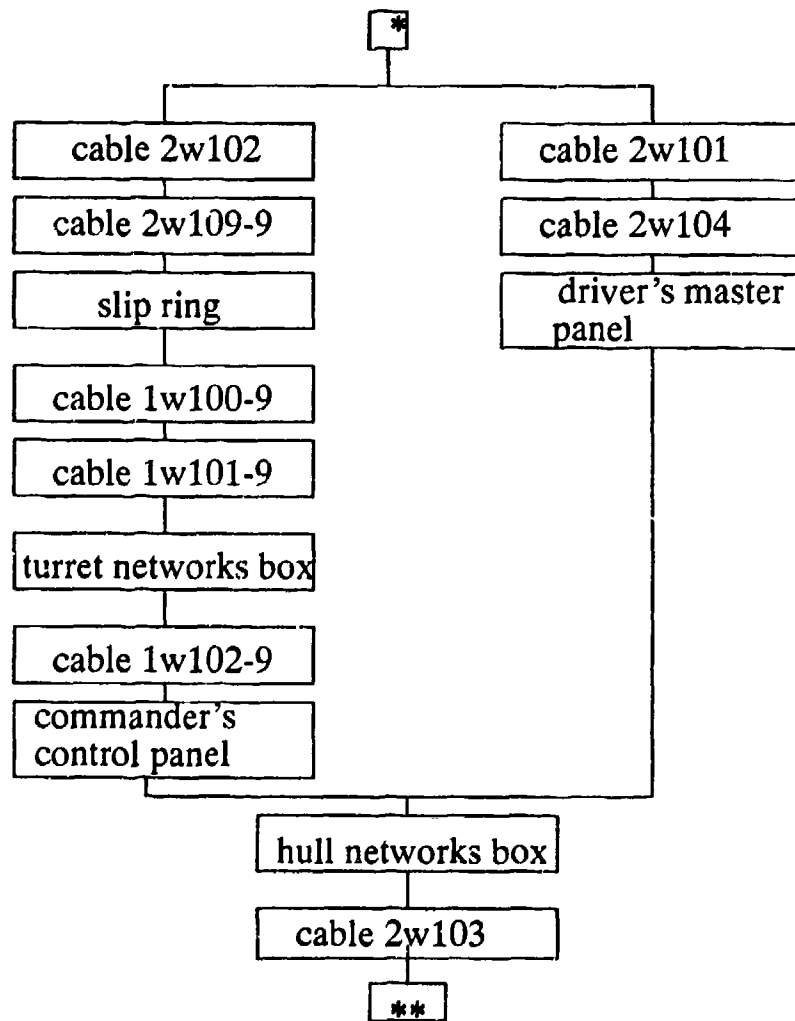


Figure 3. Master Power Control Fault Tree

**TABLE 1. Example Mobility Capability Levels for an AFV**

- \* No mobility damage
- \* Slight reduction in speed ( $<$  or  $=$  30%)
- \* Significant reduction in speed ( $>$  30%)
- \* Total immobilization

A strawman set of fault trees is developed for each capability level, starting with the criticality analysis. For the AFV, the systems developed in the criticality tree were mapped into appropriate capability levels. Different systems can map into the same capability level. For example, both engine power and vehicle electrical power, stems developed in the criticality analysis, map into the "total immobilization" capability level. Similarly, different capability levels can be affected by the same system, e.g., the electric power-hull system affects both "significant reduction of speed" as well as a firepower capability level called "unable to fire on the move". In addition, individual components which, if lost, can result in the achievement of a capability level were also included in the fault trees. The loss of the first hub right would achieve a significant reduction in speed for the AFV and was therefore included in the fault tree. Figure 4 presents the fault tree configuration for "significant reduction in speed".

Once a set of strawman fault trees is developed, the entire set is reviewed for accuracy by experts on the combat system. Their comments and suggestions may be incorporated and the fault trees updated. This finalized set is then used in the DSVM to analyze the residual capability of the combat system after it has encountered a damage mechanism.

A clear advantage of fault tree analysis for both the criticality analysis and the determination of capability level is the auditability and correctability afforded the analyst. Updates or modifications are easily made if changes are required, for example, due to combat system improvements. This process is made simpler by the automation of the fault tree process by the Vulnerability Methodology Branch (VMB) and the Logistics and Tactical Targets Branch (LTTB), both of the BVLD.

## State M2 - Reduced Speed, Significant

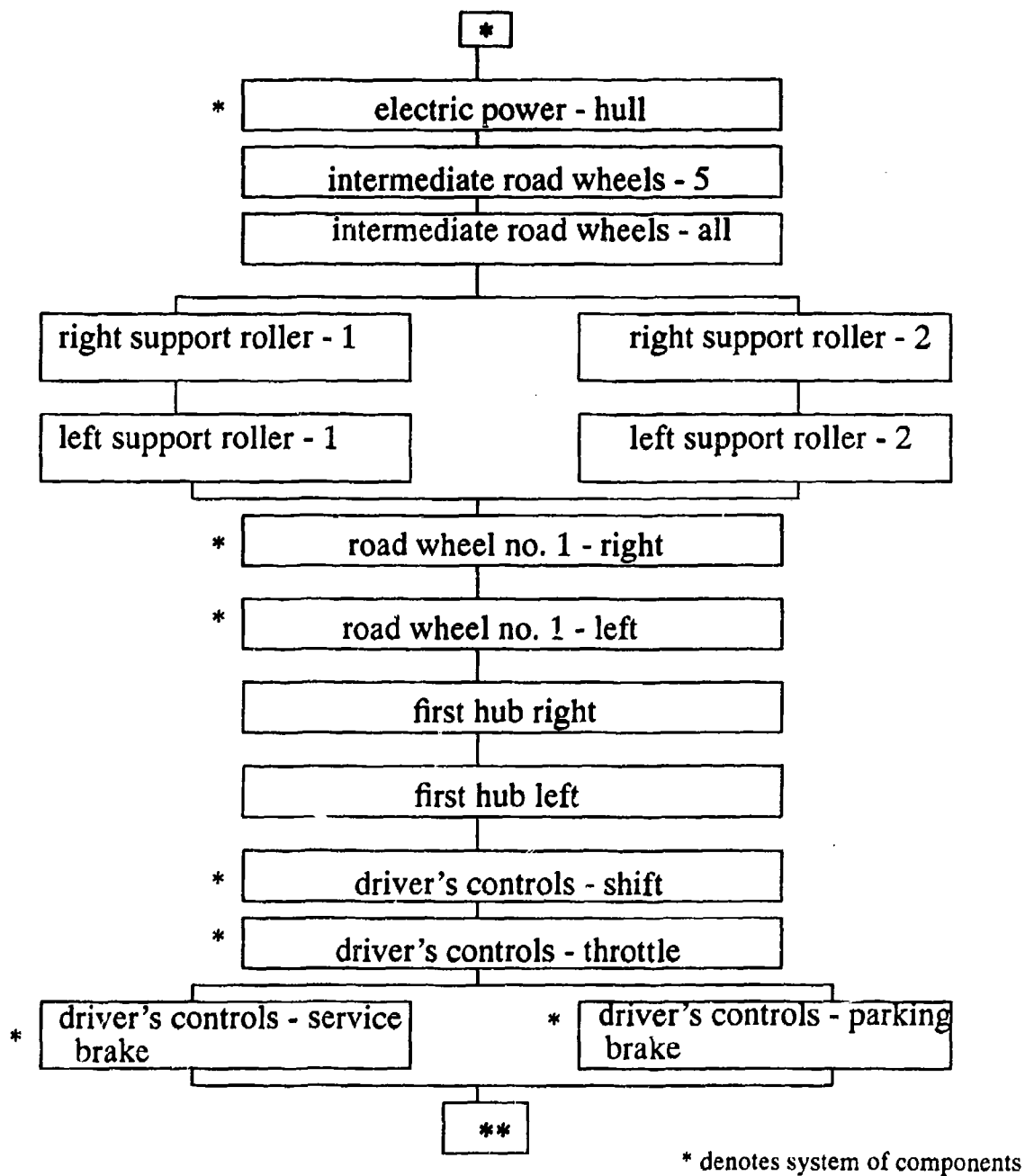


Figure 4. Significant Reduction in Speed Fault Tree

## 5. Fault Tree Automation

The process of developing fault trees was automated by VMB through the development of a computer program, called the Interactive Criticality Evaluator (ICE) (Moss, 1985). ICE allows the analyst to visually inspect each fault tree, make any necessary changes and, when satisfied, generate both a pictorial representation of the fault tree and a mathematical equation which describes the Boolean arithmetic. This equation represents the series and parallel logic and can be inserted into any computer code which requires it. For example, within the DSVM, for each capability level articulated, ICE is used to generate both the picture and the mathematical equation. These equations are then inserted in the DSVM, which uses them to evaluate sets of damaged components. Sets of damaged components are mapped through these mathematical equations to determine which capability levels have occurred. Once the appropriate files have been developed on the computer, updates or modifications can be made quickly and easily.

Further automation was accomplished by the LTTB, which created the Interactive Criticality Development Utility (ICU) (Hunt 1992). Similar to ICE, ICU allows users to quickly build fault trees in a Silicon Graphics (SGI) graphics window. ICU creates a pictorial representation as well as assembles the mathematical equations representing the fault tree. Files can be stored and edited as needed.

## 6. Additional Uses for Fault Tree Analysis

The use of fault tree analysis, however, is not limited to criticality analyses or the DSVM. The premise for this statement can be found in the V/L process structure, discussed earlier in this paper. All events, through the determination of degraded capabilities, are engineering observables or measurables; that is, one could physically observe or measure these phenomena in the field. Consequently, there are a number of additional uses for fault trees that would permit analyses across the spectrum of Army concerns for a combat system based on the same set. This would increase clarity about which capabilities are important and provide a tool for communication among the analysis community. Several such applications will be discussed in this paper. These are the 1) Reliability, Availability, and Maintainability (RAM) analyses; 2) Nuclear, Biological and Chemical (NBC) Contamination Survivability; 3) Operational Requirements Documents (ORDs); 4) comparison of analytical with experimental; and 5) force-level wargames.

**a. RAM Analysis.** An area the BVLD is investigating is the extension of fault tree analysis to address the problem of RAM. An effort is underway to identify the commonalities between the vulnerability and reliability analysis techniques. The use of fault tree analysis would not only clarify the capabilities of concern for the combat system but provide the same starting point for both vulnerability and RAM analyses. Although the "damage" mechanisms may be

different, the effect on the combat system's functionality should be the same for a given set of lost components. To investigate the feasibility of this proposition, the BVLD, in FY92, formed a working group with the Army Materiel Systems Analysis Activity (AMSAA) Reliability, Availability, and Maintainability Division (RAMD) to address problems such as familiarization with each other's analytical methods and determination of a single nomenclature for use in both V/L and RAM analyses. In addition, the BVLD and RAMD are continuing FY92 work with the U.S. Army Armor School to apply fault tree analysis to the determination of failure criteria for the M1A2 armored fighting vehicle and the Armored Gun System (AGS).

The initial premise at the beginning of this effort was that the methods for assessing the damage may take different approaches but should yield the same results. Both analyses are concerned with determining remaining combat system capability once a component becomes nonfunctional. That is, both must assess combat system damage. The V/L analyst determines the lethality of a weapon or the vulnerability of a combat system in terms of functional damage; the RAM analyst determines the reliability of the combat system by investigating functional failures. To do this, both analysts must develop an understanding of component interrelationships and relate these components to the system's required capabilities. While the V/L analyst is concerned with critical components, that is, components required to allow mission performance, the RAM analyst is concerned with all components, regardless of the effect on mission performance. For example, the commander's seat is noncritical in terms of mission performance for a V/L analysis and, therefore, is not considered during the analysis. However, a RAM analysis needs to assess the commander's seat in order to determine whether or not it meets its reliability criteria. The components of concern for the V/L analyst are a subset of those of concern to the RAM analyst. Once the capability levels are identified and the fault trees developed, each analyst could select those fault trees applying to his/her analysis.

The objective of the initial BVLD/RAMD investigation, conducted in FY92, was to determine if the two methods yielded the same results and to investigate the differences and similarities in order to determine where the two processes could be combined. The initial effort established the functional loss of the M1A1 for a given set of killed components, selected from a recent vulnerability analysis. This set of killed components was used by both reliability and vulnerability analysts to assess which functions on the vehicle were affected. Each used his normal procedures. For the vulnerability analyst, the criticality analysis of the M1A1 was consulted; a general discussion of criticality analyses was provided earlier in this report. The reliability analyst made use of the RAM-D Failure Criteria Document for the M1E1 tank as well as conversations with the M1A1 project manager. The RAM-D failure criteria use block diagrams which group components by function, e.g., mobility, fire control, etc. This allows the analyst to show the relationship between the function and the components that make up the function. A description is then developed for the block diagram, which contains

narrative representations of the basic functions followed by failure modes of the hardware associated with the function. This description reports which components cause functional loss, functional degradation, or have no effect at all.

Once the individual analyses were completed, the results were compared. Although there appeared to be, in general, no disagreement in assessed functional loss, the different processes and nomenclature made it difficult to be certain. The reliability assessment provided more specific information on functional loss, but required more effort than the vulnerability approach. Generally, the comparisons were fairly straightforward, however, some difficulties did arise. Examples are displayed in Figure 5 with a discussion provided below. The first example lists a specific cable lost. According to the M1A1 criticality analysis, the loss of this cable results in the loss of the gunner's primary sight (GPS) - thermal imaging sight (TIS). The RAM functional loss description reads "1) opens cable disconnection at the thermal receiver, thermal power unit, fire control malfunction will come on; 2) disables power between thermal power control unit and thermal receiver." This represents a fairly good comparison. However, not all were this good. In some instances, components contributed to more than one function and thus were described in more than one narrative section, depending upon the function being described. Unless the RAM analyst knew this a priori, not all lost functions may be identified. For example, one component identified as nonfunctional was the GPS, which is composed of both optics and electronics. Because these are handled separately, the RAM analyst identified functional loss relating to the optics, that is, "loss of day and night target sighting capability for accurate main/coax weapon laying using the GPS"; the electronics were not included. However, the V/L analyst, using the criticality analysis, identified four lost systems: all power traverse, all power elevation, GPS-day and GPS-TIS, and target range. A second, more common problem, dealt with matching functions selected by the analyst when developing their criteria. For example, the loss of the computer electronics unit resulted in the loss of all power elevation and all power traverse in the criticality analysis. The description from the failure criteria document read "loss of ability to calculate ballistic corrections". It's unclear if the two analysts were describing the same functions.

During the conduct of this comparison, it became clear that one set of combat system capabilities should be identified early in the developmental cycle as identification of required combat system capabilities is conducted for all facets of system analyses, to include VL, RAM, and logistics. Techniques employed have not been consistent across organizations, most likely due to a lack of realization by the various analysts/project managers of the inherent similarities, resulting in the development of different capability requirements for different applications. Developing the list of required capabilities early in the cycle would avoid the aforementioned comparison problems as well as provide the basis for all subsequent analyses of the combat system.

<u>Nonfunctional Component</u>	<u>Functional Loss</u>	
<u>V/L</u>	<u>RAM</u>	
cable 1w210-9	gunner's primary sight (TIS) (GPS-TIS)	1) opens cable disconnection at the thermal receiver, thermal power unit, fire control malfunction will come on 2) disables power between thermal power control unit and thermal receiver
GPS	all power traverse lost all power elevation lost GPS-day & TIS target range	loss of day and night target sighting capability for accurate main/coax weapon laying using the GPS
computer electronics unit	all power traverse all power elevation	loss of ability to calculate ballistic corrections

**Figure 5. Example Problems from VL/RAM Comparisons**

These examples indicate that the use of fault tree analysis could make the RAM process easier and faster. Additionally, if fault trees for a given combat system were developed jointly by ARL and AMSAA analysts, early in the analytical process, some of the differences in answers could be avoided, or more easily accounted. As a result, BVLD and RAMD agreed to a joint effort aimed at developing common standards and practices for the identification of required combat system capabilities, the components that contribute to each capability, and the interrelationship of these components to overall system functionality and impact when the component (or subassembly) is lost or partially lost. This effort is intended to develop a standard technique for use by all organizations. Development of this technique will enhance the Army's ability to provide detailed and consistent system capability requirements across the spectrum of analyses. In addition, savings can be identified in terms of both time and money by the reduction of duplication of effort. It is anticipated that this effort will be the starting point for all subsequent combat system analyses to include vulnerability, RAM, logistics, survivability, and effectiveness.

**b. NBC Contamination Survivability.** The BVLD performed an analysis to determine the effects of the chemical contamination/decontamination cycle on component hardness (Juarascio 1992). One objective of this effort was to assess the feasibility of utilizing the conventional vulnerability tools, i.e., fault trees, ICE/ICU, and the DSVM, in conjunction with the Chemical/Biological Information Analysis Center (CBIAC) database, and if possible, develop a test case example to illustrate the form of the analytical results. The M1A1 tank, the vehicle analyzed in the initial DSVM analysis, was chosen as the illustrative example for the purpose of identifying needed modeling and database improvements to support a robust assessment of the chemical contamination hardness criterion. The use of fault tree analysis and the DSVM lent themselves to this type of analysis because, while the damage mechanisms which cause loss of system functioning vary between chemical and conventional threats, the resultant degradation in system performance, given the loss of the same set of components, should not be different.

Hardness is defined as the ability of a system to withstand the material damaging effects of NBC contamination and the procedures and agents required to decontaminate the item. Materiel developed to perform mission-essential functions shall be hardened to ensure that degradation over a 30-day period of no more than 20% (or other value designated by the combat developer based on approved rationale) in selected quantifiable mission-essential performance characteristics is caused by five exposures to NBC contaminants, decontaminants, and decontaminating procedures encountered in the field (AR 70-71 1984).

The idea was to evaluate different events (either contamination of the item or the subsequent decontamination) and to determine the amount of degradation to susceptible system materials and thus the probability of the critical component failing. The analysis was limited to exterior components for a number of reasons.



First, as this was a test case, the problem was simplified by the exclusion of interior components. Most importantly, though, it eliminated the classification restriction associated with the description of M1A1 interior components.

The exterior components analyzed in this test case were the following: commander's sight, commander's vision blocks, gunner's primary and thermal imaging sights. Of interest was the effect of the chemical agent on the physical properties (transmittance, haze, and resistance to optical abrasion) of the glass portions of these components.

The components were assessed as either failed (combat ineffective) or not failed (combat effective) based on achieving some predefined critical property degradation given specific system application. Using this information, component damage vectors were derived for use in the DSVM. The DSVM mapped these failed components through the capability levels to determine which degradation levels were achieved. The results of the DSVM analysis could then be used to identify whether or not the vehicle met the hardness criterion or to identify benefits of choosing different material types. Although still in progress, initial results of this analysis indicate that the conventional methodology can be adapted for chemical contamination hardness assessment, given sufficient data for the Level 1 to Level 2 mapping become available.

Although not complete, some conclusions can be drawn from this analysis. The prediction of the degraded state of a system; given contamination and decontamination and their estimated frequency of occurrence, given the conditions of evaluation as set forth by the hardness criterion; would allow the project manager to quantify system degradation and provide a means for determining effective ways to maximize system hardness. Establishment of a baseline set of damage vectors and variations on the estimated probabilities of failure as a function of material application could serve to show how changes in material choice would change the baseline frequency distribution. Additionally, variations on the design of the system to introduce system redundancies (as reflected by changes in the fault tree description) could serve to quantify changes in system hardness independent of changes in material choice when perhaps the option to utilize different materials does not exist.

Development of this methodology for NBC contamination survivability assessment would provide an analytical tool for the system designer in determining which component losses will result in failure of the system to meet the NBC contamination hardness criterion. It may then be used to determine improvements in overall system survivability given appropriate changes in material applications or perhaps in system design.

c. **ORDs.** An additional application of fault trees is the determination of performance criteria for ORDs. Per DOD 5000.2M, an ORD is a formatted statement containing performance and related operational parameters for a proposed concept or system. The initial ORD will describe each concept proposed at Milestone I to include terms of minimum acceptable requirements that define the system capabilities needed to satisfy the Mission Need Statement. The ORD is updated and expanded for Milestone II to include thresholds and objectives for more detailed and refined performance capabilities and characteristics. These updates are based on the results of the trade-off studies and testing conducted during Phase I (Demonstration and Validation). The ORD is then used to develop the system's requirements for contract specification through each acquisition cycle.

One of the major objectives of the ORD is to define the required performance capabilities and requirements. These definitions are to include a performance objective which represents a measurable, beneficial increase in capability or operations and supports the minimum acceptable level specified in the document. Historically, though, these performance objectives have been defined in terms, usually probability of kill (PKs), which are both physically unmeasurable and sufficiently vague in quantification. Because of these inherent problems, definition of the requirements in terms of the system's required capabilities would provide well-defined, measurable performance objectives. As an example, the application of the DSVM approach to the Advanced Field Artillery System (AFAS) will be discussed. This work was initially performed at the direction of the Program and Vulnerability Assessment Office of the Secretary of the Army for Research, Development, and Acquisition (SARDA). (It should be noted that this approach works just as well for lethality [i.e., missiles] as it does for vulnerability/survivability of combat systems. Thus, the use of the term "combat system" implies any system which can be described in terms of required capabilities.)

The AFAS is the future self-propelled howitzer, designed as the replacement for the M109A6 Paladin. The proposed ORD for AFAS was reviewed with selected performance requirements rewritten in terms of required capabilities. As neither the firepower nor the mobility requirements were described in terms of physically measurable quantities, suggestions were made as to how these requirements could be rewritten. Firepower, for example, could be expressed in terms of lower and upper bounds of an acceptable level as shown in Table 2.

**TABLE 2. Example Firepower Requirements**

Requirement: Rate of Fire

Acceptable levels:

Upper bound: at least 12 rounds/minute for 5 minutes

Lower bound: not less than 6 rounds/minute for 5 minutes

The same type of physical, or engineering, metric could be applied to the mobility requirement. For example, speed could be defined in terms of the required (and desired) level for different environments, i.e., at least 40 miles/hour in European rolling hills or 25 miles/hour in Southwest Asian desert.

The quantification of the requirement in terms of engineering metrics permits easier evaluation as to whether or not the requirement has been met. The benefits of this approach are numerous. First, the requirements are expressed in terms of capabilities which can be explicitly measured and which are separated into the different capability categories (i.e., mobility, firepower and acquisition). It provides a means for the user to prioritize the capabilities most worth preserving as well as provides greater insight into the military utility of the system. Most importantly, it provides greater clarity as the user and developer of the system discuss trade-offs between what capability is wanted versus what can be affordably built.

**d. Analytical Versus Experimental Comparisons.** Most of this paper has focused on the analytical techniques employed in vulnerability modeling. However, important applications in the area of experimental data also exist. The approach promulgated in this paper provides an excellent means by which to evaluate both live fire experimental data and potential shot locations prior to actual firings. Pre-shot predictions allow the evaluator to select the most meaningful shots; thus shots which may provide minimal data can be eliminated, or shots which may result in catastrophic loss of the system can be postponed until the end of the shot series.

Most importantly, a combination of experiments and modeling can be employed to maximize the characterization of system performance while minimizing the cost of such characterization. To do so, modeling must be developed such that it parallels the testing process. This, in fact, is the policy of the BVLD as evidenced by the development and promulgation of the V/L Process Structure discussed earlier in this paper. When the modeling parallels testing, one can model a number of threat/target interactions and then do selective testing to see how well the modeling parallels the testing outcome.

The use of fault trees allows one to get to Level 3 in the V/L process as well as provides an interim step between Levels 2 and 4. Modeling from Level 2 to Level 4, as done with the traditional Standard Damage Assessment List (SDAL), does not parallel live fire testing (LFT). Thus, one cannot relate the damage from the LFT to the loss of function value provided by the SDAL or even to battlefield utility; there is no direct comparison between the two. The fault trees, in tandem with the V/L process, provide the means for this direct comparison; it is the inclusion of Level 3 which makes this possible.

e. **Force-Level Wargames.** The modeling of system functionality with fault trees, in concert with the DSVM, also has consequences for force-level modeling. It permits a more accurate portrayal of the system's remaining capabilities as a result of nonfunctional components, either through combat damage or failure. As currently modeled, the system is either fully functional or fully non-functional. A more realistic approach would be to model the system as still functional but in a degraded operational mode. This would result in a system remaining in the engagement longer and possibly affecting the outcome of the game. In addition, information from Level 2, component damage, would provide detailed information on damaged parts, thus providing more accurate data on spare parts requirements and the need for battle damage repair. A joint effort between BVLD and the Training and Doctrine Command (TRADOC) Analysis Center (TRAC) at White Sands Missile Range is currently investigating the inclusion of DSVM metrics in JANUS-A and the resulting affect on the wargame. This effort will provide a clearer picture as to the benefits of fault tree analysis in force-level models.

## **7. Future Requirements**

It is envisioned that the process discussed in this paper can be improved by the inclusion of a continuous function representing component functionality. Although better than previous models, the "go, no go" decision of component functionality is not realistic. A component can suffer damage and still continue to function. For example, how does one handle the problem of a crimped cable when the cable is still functioning though not at 100%. The modeling of such phenomena will be part of the future effort to expand both fault tree analyses and the DSVM as well as the extension of these models to the areas discussed in this report. Current thinking is to allow for additional Boolean arithmetic such as "exclusive or", "maximum" and "minimum". This would permit more detailed and realistic modeling of the combat system and its critical subsystems. In addition, instead of separate fault trees representing capability levels, one extensive event tree could be developed to represent the entire system; branches/nodes could then be weighted according to some mission under consideration. (Note, the event tree would include fault trees representing various system capabilities.) Figure 6 is provided as an example of how this system event tree might look.

## **8. Summary**

Fault tree analysis is a critical part of the vulnerability/lethality framework. It provides the fundamental information on a combat system's subsystem/component interrelationships and its required capabilities as well as a starting point for all subsequent analyses of the system.

As this report discusses, fault tree analysis provides an ideal tool for analyzing a combat system's functionality throughout the various levels of the V/L process structure. To this end, it provides an ideal device for communications

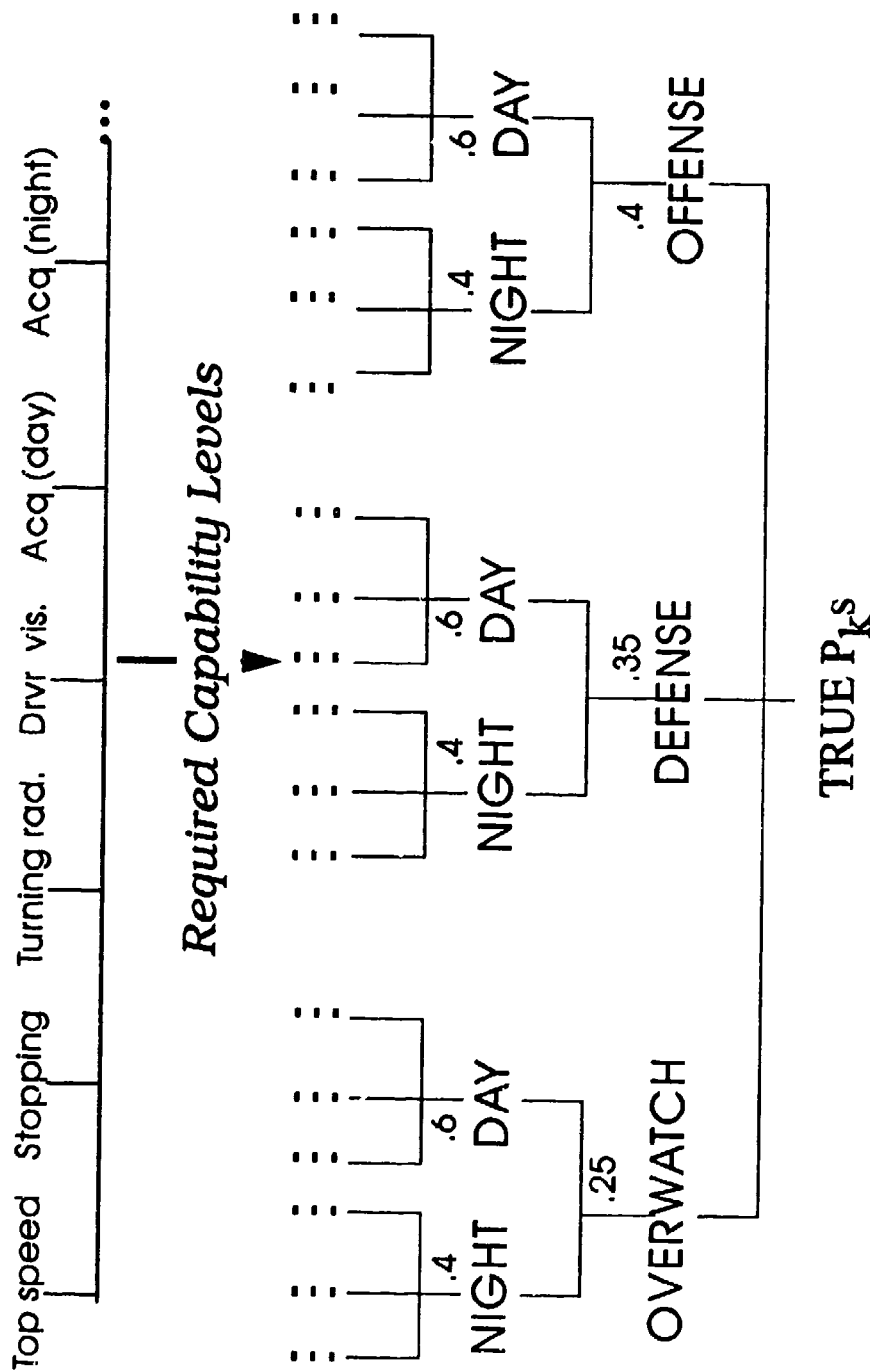


Figure 6. Example of Single System Fault Tree

between concerned participants. The initial effort required to define the fault trees clarifies the required functions of the combat system as well as reduces the need for subjective judgements later in the process. This, in turn, leads to fewer misunderstandings, particularly before major milestones or reviews. The approach also allows V/L modeling to parallel the testing process. As a result, at any level, the modeling can be reviewed for its adequacy in predicting live-fire testing outcomes. In addition, many types of testing may be reduced to determining which trees are broken under initial conditions of interest.

Finally, both fault tree analysis and the general V/L process structure have applications in areas outside the realm of vulnerability/lethality, as evidenced by the discussions within this report. The ability to clarify the operational requirements of a system by identifying its required functions provides a sound basis for communications between the user and the developer throughout the acquisition life cycle of the system. The same analytical approach can be applied to RAM and Battle Damage Repair Analysis (the subject of a forthcoming report) which allows one to evaluate the major aspects of the acquisition cycle using the same process. This overall improvement in communications and analysis can only improve the Army's ability to provide timely, credible analyses.

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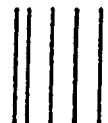
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